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Wave electrical energy systems: Implementation, challenges and environmental issues

Arqam Ilyas [a], Syed A.R. Kashif [a], Muhammad A. Saqib [a,*], Muhammad M. Asad [b]

[a] Department of Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan
[b] Flexible AC Transmission Systems (FACTS), ABB Group, Saudi Arabia

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ABSTRACT

With the world's predicted wave-power capacity of 1–10 TW many projects are being implemented around the world and have brought in many useful insights and innovations during their implementation. This paper discusses the major projects, the world over, for the generation of electrical power from wave energy. The literature for these projects is reviewed extensively to describe the waves as potential sources of electrical energy: different challenges that these projects faced and how these challenges were tackled are also discussed. Methods for the wave-energy conversions for each of these projects will also be critically reviewed and the economic and environmental aspects are also explored. The paper aims to summarize the technologies, challenges and technical considerations for harnessing wave energy to set a path for future development. The experiences of the previous projects and the lessons learnt from them can be very helpful for the future development of similar projects: in this context the Perth Wave Energy Project is presented and discussed in detail.

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* Corresponding author.
E-mail addresses: arqamilyas@live.com (A. Ilyas), abdulrahman@uet.edu.pk (S.A.R. Kashif), saqib@uet.edu.pk (M.A. Saqib), mateen.asad@sa.abb.com (M.M. Asad).

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1. Introduction

An increased concern about the negative effects of generating electricity from fossil fuels has forced the world to look towards alternative and sustainable sources of electricity production. The electric-power generation from wind and the sun is being realized at a reasonably fast pace. But to meet the rapidly growing demand for energy there is a need to discover further sustainable resources. Wave energy has the highest energy density among all renewable energy sources known presently, low environmental impact especially for the near-shore devices, is available that matches the electricity demands in temperate climate, have an availability percentage as high as 90% and can travel large distances without significant energy loss [1]. Thus wave energy offers considerable environmental and technical advantages. But wave energy is applicable in only a few regions in the world and requires mostly unproven technologies. However, the total potential of wave energy has been estimated between 0.2 and 10 TW which, even on its lowest estimate, is able to satiate a major portion of the world's demand for energy [2].

Wheels have started to turn and research is well on its way. The UK was the first country to take off in the race; wave hub project was established in the west of Cornwall and the European Marine Energy Centre (EMEC) was established at Orkney, with facility for grid interconnection to mainland Orkney, to encourage commercial development and field testing for technology with the potential of producing electricity [3].

Sweden followed suite with the Lysekil project, headed by the Swedish Centre for Renewable Electrical Energy Conversion in Angstrom Laboratory at Uppsala University. The Uppsala University Wave Project, upholding the Swedish tradition of innovation, implements directly-driven linear generators which have less complex mechanical components and thus less operation and maintenance costs instead of using the conventional systems using hydraulics [4] and turbines [5] which use a large number of mechanical parts and have high maintenance costs [6].

The Perth Wave Energy Project, headed by the Carnegie Wave Energy Ltd., Australia, kicked off in 2012. It seeks to implement the CETO technology which drives pressured water on shore to generate electricity [7]. CETO is ideal for cogeneration and thus, can generate electricity as well as help produce drinking water and hence represents another breakthrough [8].

But that is not all. It has been estimated that in the Caspian Sea, the wave energy potential is around 5–14 KW/m [9]. Similarly the seas around China are also estimated to possess a wave energy potential of 4–12 KW/m [10]. The UK is considered as a pioneer in WEC technology and has many early innovations in the field. These projects have been extensively reviewed and the literature related to them is an excellent source of information for challenges, benefits, WEC technology and generator technology related to wave electrical energy systems. The Swedish Lysekil project built on the experience gained in the projects in the UK, especially in linear generators for WEC, and thus shows that there is opportunity to generalize challenges, technologies, process etc. to facilitate rapid implementation of WEC technologies. Furthermore the literature for Lysekil project provides useful insights on the wave theory and mathematical models applicable to implementation of WECs. During the Lysekil project the environmental impact of WECs to surrounding ecosystem was also observed. The contingencies and challenges that these projects faced, and the technologies that were developed have been used to evaluate the most suitable technologies to be implemented in the Danish north sea and the Chinese seas [10], [11].

Therefore, it can be seen that it could be extremely helpful to summarize the experiences from the projects that have already been implemented, as they can help implement future projects. In fact, Kofoed et al. [12] have developed a comprehensive methodology for doing sea trails of existing WEC technologies and collecting and filtering data, in order to determine the optimum technology for implementation. It can be even more helpful if common technological, environmental and economic challenges can be summarized, which can serve as a guide for planning resources as well as activities.

Therefore, in this paper, some of the projects that have been implemented all around the world are discussed and an attempt has been made to outline the major challenges that wave energy technologies and projects can face. Environmental and economic insights shall be presented and finally the Perth Wave Energy Project shall be presented to show how experiences from previous projects can be used to ease implementation of new projects and technologies.

2. Review of the wave energy

2.1. Energy from the waves

Ocean waves are generated by blowing winds and the resulting sea swells transport energy from storm centers to distant shores [13]. Waves absorb energy from winds blowing over larger areas. This means that waves are more predictable than winds and the waves keep rolling even after the wind abates. However, since the variations in forces and power involved are huge the system must provide electricity at average ocean climate and also survive extreme storms. So the major challenge is to provide a system which is economical and also strong enough to survive the extreme ocean climates [14]. Wave energy can be tapped off-shore and also near the shore. Off-shore devices have an advantage of providing less visual impact and wave power available off-shore is also greater. Off-shore devices have

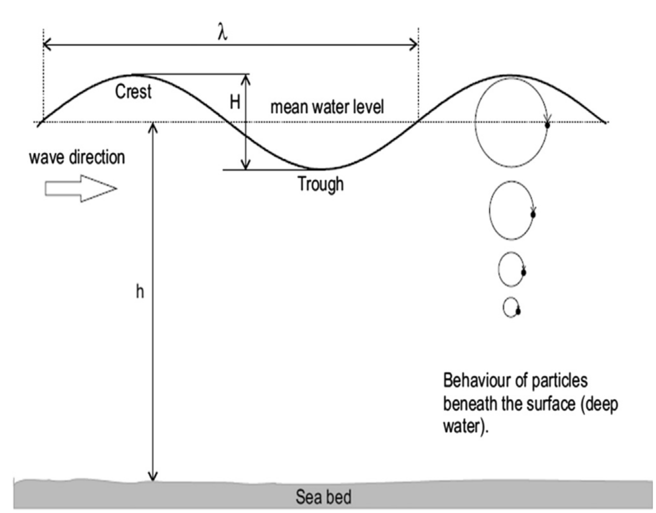

Fig. 1. Representation of a wave [6].

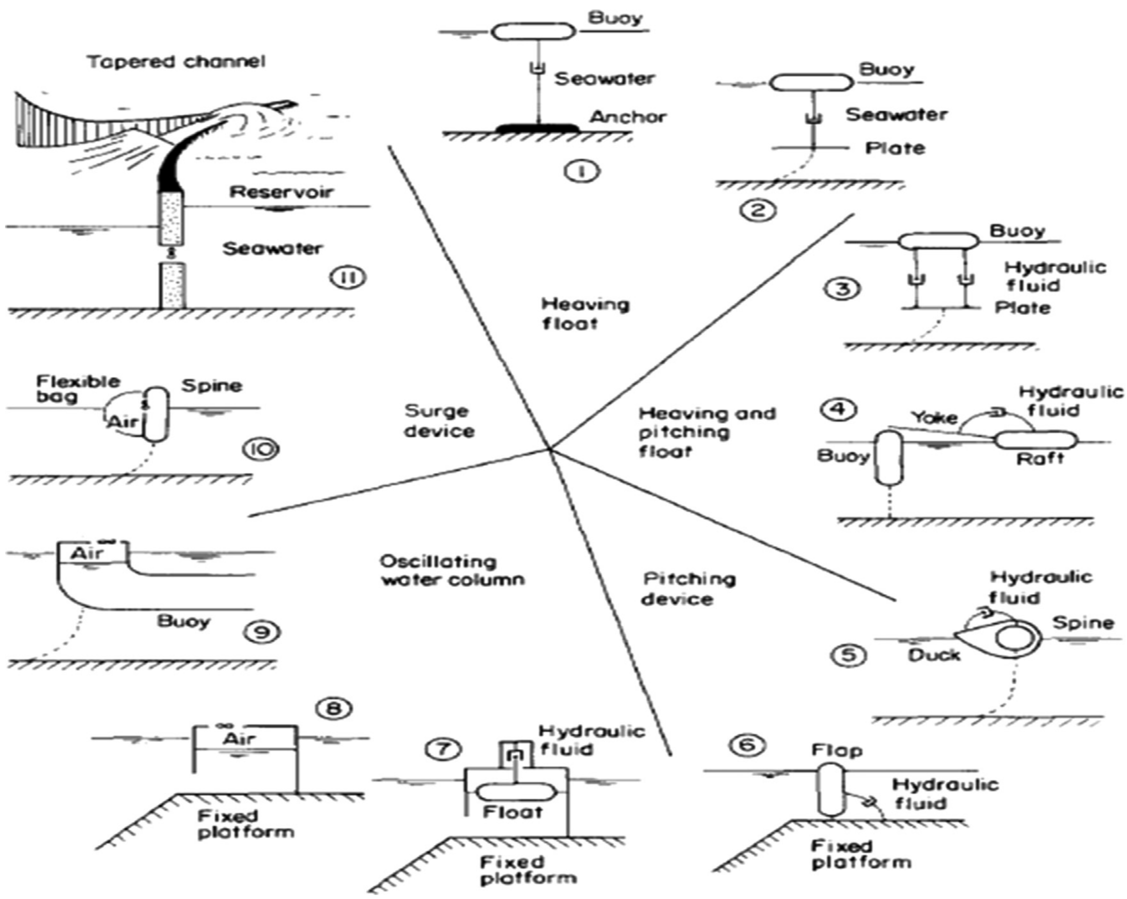

Fig. 2. Some of the proposed wave electricity converter technologies [13].

a possibility of having less accessibility for maintenance but they are easy to construct and have fewer chances of corrosion and exposure to extreme wave forces, especially if they are submerged [13].

Waves are described physically by their length, λ, and height, H, as shown in Fig. 1. If $\lambda < 0.5\ H$ and water is deep, due to oscillatory movement of wave particles, 95% of the energy in the waves is available between the surface and a depth equal to quarter of the length. However the wave theory applicable is dependent on the ratio of wavelength and height [6].

Typically the average value for the natural power transport J per unit width of the progressing wave crest varies between 0 and100 kW/m at latitudes of 40° to 65° and decreases as we move towards the equator or polar regions. In the tropical region the average is between 10 and 20 kW/m [13].

2.2. Wave energy converter (WEC) technologies and their classification

There exist more than a thousand different WECs in the literature from floating, oscillating, and bottom-standing to submerged types. In the patent literature there are more than a thousand different proposals for the utilization of wave energy. Fig. 2 gives an overview of different types of proposed WECs [13].

Despite the variations, all WECs can be roughly categorized in three major types. The first type is attenuators which lie in perpendicular to the wave front and 'ride' the wave. *Pelamis*[1] is an example of an attenuator type WEC. The second type is called *'point absorbers'* (PAs) which are floating structures that heave up and down with the crests and troughs of the waves driving a generator attached to them. The Uppsala University WEC, which shall be discussed in detail, is a type of PA. The third type is called submerged devices that work by exploiting the pressure differential and terminators which lie parallel to wave fronts and intercept the waves [1].

But for simplicity WECs are classified into three categories based on the mode of operation; oscillating water column (OWC), overtopping devices and wave activated bodies. OWC forces the water into a chamber and drive a turbine by varying the pressure of the air inside the chamber. Overtopping devices are the devices in which the waves are spilled over guided structures to cause change in potential energy which is converted to electricity. Finally, wave activated bodies are the groups of devices that move along with the wave motion to drive a generator. They can heave, surge, roll or pitch based on their construction [6].

The categorization mentioned above can be used to classify all types of devices. For example, a point absorber is a type of wave activated bodies which float on the surface and move up and down and drive a generator on the sea bed. Similarly submerge is also considered as a wave activated body. They have a fixed air-filled cylinder chamber with a movable upper cylinder. The change in pressure above the upper cylinder by crests and troughs changes the pressure of air inside the chamber which can be utilized to drive a generator. Some point absorbers can also be classified as OWC devices, especially if they are built near shore [1]. Fig. 3 summarizes the three categories of WECs [6].

2.3. Power take-off (PTO) system

2.3.1. Generation of electricity

Even though all generators convert mechanical energy to electrical energy and consist of a moving part known as rotor in rotating

[1] Pelamis Wave Power, http://www.pelamiswave.com/ Accessed 2013-09-21

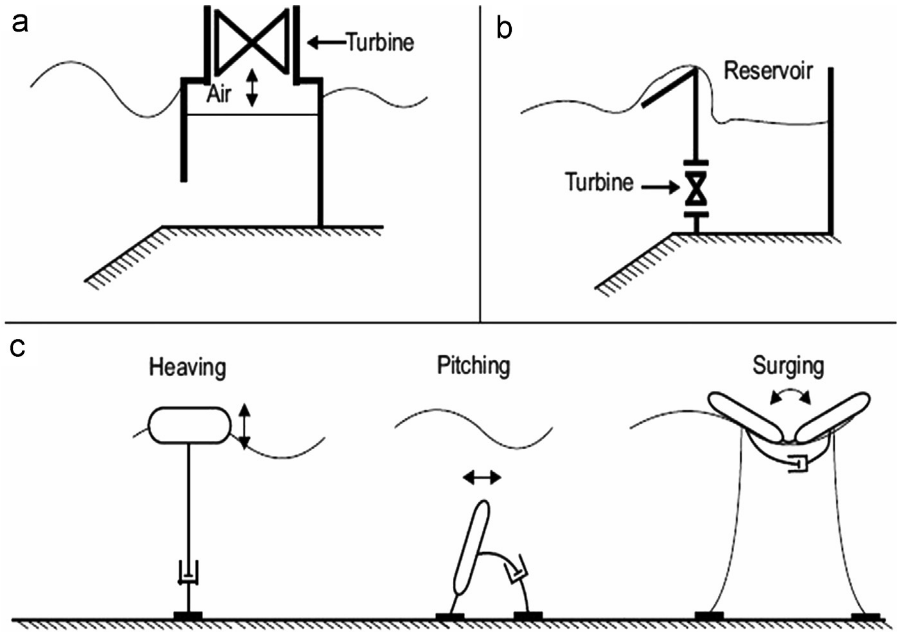

Fig. 3. Wave electricity converter can be classified in a) oscillating water column, b) over-topping devices, c) wave activated bodies.

machines and translator in linear machines and also has the magnets mounted on it, and a static part known as the stator, there are many different proposals on how to design a WEC and what kind of generator (linear or rotary) should be used [6].

The basic principle for all generators is Faraday's law, which states that a changing magnetic field in a coil will induce an electromotive force E in that coil:

$$e = -N\frac{d\varnothing}{dT} \tag{1}$$

Where '*N*' is number of coil turns and ϕ is the magnetic flux. The major difference for a rotating generator and linear generator is that for a rotating generator *N* will always remain constant but for a linear generator the translator can move out of the stator which can reduce the active area of interaction between the translator and stator and the voltage will drop. Hence, the dynamics of the generator will change and the length, stroke and equilibrium position of a translator and the output load become important [14].

2.3.2. *Utilizing electricity from WEC*

2.3.2.1. Energy storage. Wave energy, like all forms of renewable energy is intermittent. Hence, energy storage systems are vital in a wave energy power take off (PTO) system to mitigate fluctuations and aid grid integration [1], [15]. Steven H. Salter, considered as a pioneer in wave energy and credited with the invention of the Edinburgh Duck, suggested in reference [16] that about 100 s of energy storage will be to mitigation flicker and support grid integration. A proposed method is to connect different means of energy storage to a generating system, for example, a flywheel, compressed air energy storage system, fuel cell system, super-capacitors etc. Details for the application of super-capacitors, doubly fed induction generator and Vernier hybrid generator for WECs can be found in references [17–19] respectively.

2.3.2.2. Power flow control and grid interconnection. The interconnection of distributed generation sources to the grid is governed by IEEE 1547-2003 which specifies the requirements for design and interconnection to the power systems of distributed generation sources. In there may be local bylaws that govern interconnection but generally the smaller the size of the power source the fewer the regulations that will be applied to it. The idea of these regulations is to improve grid stability by minimizing the impact of these sources on the overall system. The parameters that are used to characterize voltage disturbances are voltage unbalance, flicker and voltage variations, harmonics, and transients. Voltage unbalance refers to the limit of deviation of the phase angles of each of the three phases to a certain extent. Flicker, also related to voltage variation, is the variation in the visible lighting. But flicker is not the only disturbance as a result of voltage variation. Harmonics, measured in terms of total harmonic distortion (THD), are all frequencies other the fundamental frequency and have a lot of negative effects if they are not controlled properly. Transients are temporary and fast disturbances; resulting from lighting, switching etc., which can cause huge voltage variations [15].

As the voltage generated by a WEC is of varying amplitude and frequency it is first converted to DC voltage and then inverted into an AC voltage of desired amplitude and frequency. Three-phase *voltage-source converters* (VSCs) are ideal for this application [15], [20].

By using multi-level inverters the total harmonic distortion can be reduced [15]. Insulated-gate bipolar transistors (IGBTs) are commonly used in power electronic converter applications as they combine the high switching capabilities of a MOSFET and reduced losses of a BJT [15], [21].

The voltage of the DC link capacitor is very important for the function of VSC's arrangement. We can control the power reversal by controlling the voltage at the DC link in such a way that the flow of current is reversed at the DC link. We have an outer DC voltage control loop and an inner input current control loop and the voltage error of the DC link is used to generate the input current command for the current loop [20].

As pulse width modulation (PWM) can control the active and the reactive power so it provides the DC voltage regulation as well as the power factor correction and takes balanced input current. The PWM method is a common method for the control of power electronic components. Keyhani et. al. have extensively discussed the applications of inverters in grid interconnection of distributed

generation resources and the challenges and considerations associated with it [22].

3. Challenges

As described, wave energy shows a lot of promise. However, just like wind and solar wave energy also has some challenges associated with it which have to be overcome for successful implementation of WECs. In this section these challenges will be discussed and it shall also be described how these challenges can be overcome.

Firstly, the waves produce an intermittent low frequency (about 0.1 Hz) and high force output, and the generator must be capable to be driven and produce an output acceptable to the grid. Secondly, in offshore locations especially, the wave motion is random and unlike near-shore devices, it is almost impossible to predict the predominant direction of the wave. To capture energy from these irregular waves is another challenge. Furthermore, as mentioned before, the WEC must be able to operate on normal conditions and also withstand the extreme conditions, during which the available forces can be as high as 100 times. This provides serious engineering challenge to design a device that must be robust and efficient. Also, the sea water is a highly corrosive environment and the WECs must be designed to be minimally affected by it. Last but not least, due to a large number of environmental and technical challenges associated with the sea, the research focus is diverse and survival at sea and performance at sea has received considerable attention than actually using the motion to generate electricity [1].

The maintenance of the installed devices presents a challenge in itself. Maintenance being expensive, time-consuming and risky should be minimized to preferably annual inspections or even less than that. On-shore devices have easier access but suitable locations are fewer and civil work execution becomes difficult on the wave-exposed shore. The construction of off-shore devices in a shipyard is easier. Also, power available on-shore is much less than that on off-shore and the visual impact of on-shore devices is much higher. Submerged off-shore devices have even less access for maintenance but they are more exposed to corrosion and extreme wave conditions [13]. Alternatively, there are near-shore devices which are operated in relatively shallow water. It must be noted, however, that the threshold of deep water is different in different sources. Another advantage with near-shore devices is that they can be placed on the seabed and have a sound base, but as for on-shore devices, the available power is much less than from off-shore deep-water devices. The construction and maintenance of near-shore devices is more economical, however, they have to withstand stronger wave forces during extreme conditions and some argue that the floating off-shore devices offer a greater structural advantage. It is also important to note that the maximum power available in a wave is located between the surface and one-quarter of a wavelength below, as mentioned in the theory section [1].

The UK can be considered as a pioneer in the field of wave energy. The *Pelamis*, an off-shore device, is close to commercial operation and the *Wavegen Limpet*[2], an on-shore OWC device, is already operational. There are a number of companies working on wave energy, and universities and educational institutes are equally contributing with research. University of Edinburgh is an active contributor and the Wave Power group at this university is credited with developing the Slater's nodding 'duck' device which is reported to absorb wave energy one hundred percent. Much research is being done on how to convert wave energy into electricity and this has revealed a unique set of challenges [1].

[2] www.wavegen.co.uk, Accessed 2013-09-21

3.1. From wave energy to electricity; the power take-off (PTO) system

Most of the projects in the UK utilize conventional high-speed rotary electrical generators as PTO. The most significant challenge is how the WEC should drive the generator. It has been found that for OWC application the generator is similar to that of wind turbines. A doubly fed induction generator (DFIG) is the generator of the choice for wind-turbine applications but it provides a significant challenge in terms of maintenance which makes the operation and maintenance of WECs, especially off-shore ones, more difficult. As in case of all moving systems the end-stop is an important component of the PTO. Extreme forces, which result in extreme oscillations, can seriously damage the cylinder and must be mitigated. It is recommended to use high-stroke actuators but the mass and cost must be considered by the structural engineers. In addition the buckling of extended stroke is also an issue particularly if side loads are present [1].

For a WEC application, sea water is safe and environmental-friendly fluid to drive the generator but the seawater has many unpredictable constituents and abrasive particles can damage the generator, particularly in near-shore applications [1]. Using air as a fluid is one way to tackle the challenge. The advantage is that the slow-motion waves can be converted to high rate of air flow. Alternatively, a hydraulic system can be used to convert slow motion of waves to high flow rate of the fluid to use a hydraulic system. They are especially useful for WECs applications which require less size and weight. However, fluid containment is the primary concern for safe operation for such systems. The UK Department of Trade and Industry recommends using water or other environmentally acceptable fluid. The Pelamis WEC uses fluid that is biodegradable in the marine environment combined with double layered egress/ingress protection to minimize fluid leakage [1].

3.2. Efficiency

Efficiency is vital to properly harness the wave energy potential. By using coupled variable displacement pumps and motors, nominal efficiency of the PTO is around 80 percent. The efficiency drops if the generator operates away from the ideal operating point and that is where the challenge is. Hydraulic systems have a higher efficiency rating but care must be taken that the PTO will operate at a fraction of this rating most of the time. In addition, it is suggested to use check valves and throttle valves to rectify and control the flow respectively but the pressure drops in their orifices that tends to reduce efficiency due to the power loss [1].

3.3. Importance of investigating the sea surface

Like all wave energy projects, it is again important here that the structures must survive in the extreme harsh climates and also operate efficiently under normal conditions. In fact two OWCs, one installed in Sakata, Japan, and the other installed at Trivandrum, India, were irreversibly damaged by waves [9].

The power in waves varies as high as 50 times in seconds, peak power handled by the WEC is much higher. So survivability is not only about handling the extreme sea conditions but also the peak power during normal operating conditions. But the technology must also be less complex to have minimum need for maintenance and must be able to operate for a longer period of time to be commercially interesting. That is what the team of the Lysekil Project hopes to achieve [23].

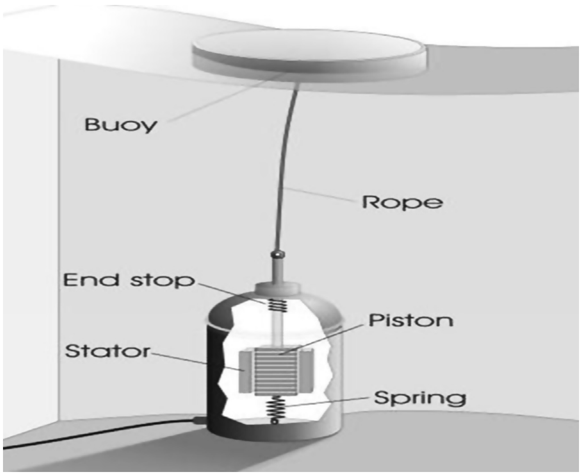

Fig. 4. Lysekil wave electricity converter and generator.

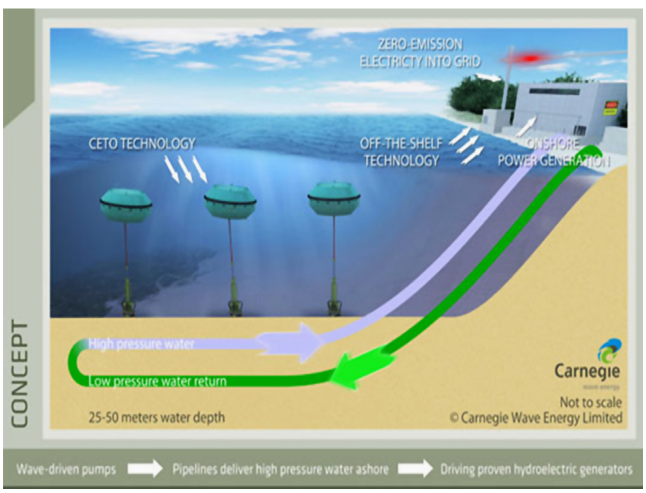

Fig. 5. CETO power schematic [28].

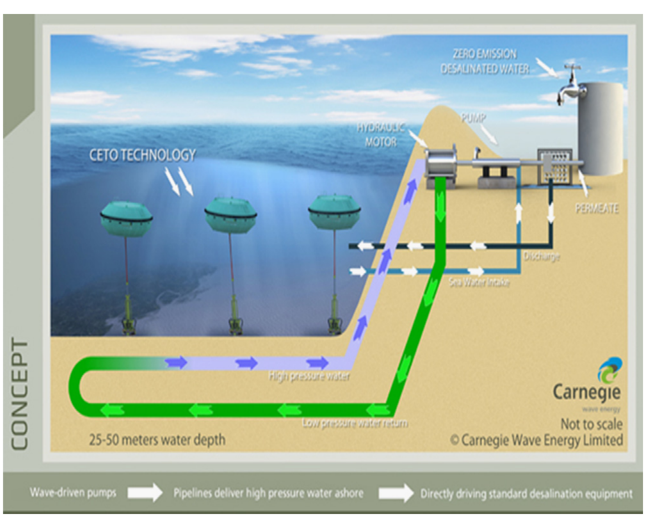

Fig. 6. CETO as cogeneration [28].

A good project should always consider all factors involved. Hence, a survey of the conditions at the bottom was conducted by SGU (Geological Survey of Sweden). It was found out that the bottom at the center of the test site consists of an even surface inclined slightly towards the west. The water depth is between 24 m and 25 m. The material at the bottom is about 1 m thick

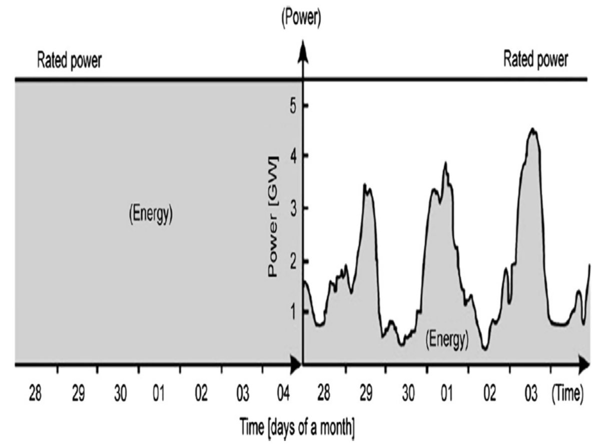

Fig. 7. Comparison of available energy, which is the shaded portion, of a non-intermittent and intermittent power sources [29].

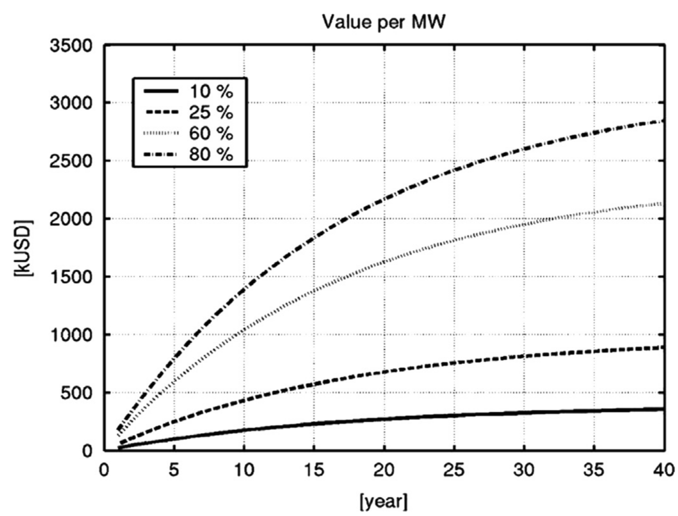

Fig. 8. Curves representing present values of investment corresponding to a degree of utilization of 10%, 25%, 60% and 80% for interest rate = 6%, adjusted cost = 0.003 USD/kWh and production price per unit energy = 0.03 USD/kWh [30].

sandy silt with smaller areas covered with rougher material. All permits to run this site till the end of 2013 when the equipment has to be decommissioned [3].

3.4. Linear generator

The first linear generator was implemented in 1970s. It consisted of a simple arrangement of a permanent magnet linear generator at the sea bed, connected by a rope to an oscillating point absorber at the surface. Various assemblies of the generator have been installed and tested in Norway and Denmark in 1980s and 1990s. The principle used by all of these arrangements is the same, with slight variations. The system tested in Denmark supplied high pressure water to the hydraulic turbine in the PTO by using a piston, but this system was discontinued [24].

A WEC developed by the Oregan State University in USA, consists of permanent magnet linear generator, which is driven directly by a point absorber connected by a rope. To limit the motion of the point absorber in the vertical direction, bearings have been used [24]. Similar arrangement was also developed by Uppsala University and implemented at Lysekil.

The Swedish Centre for Renewable Electric Energy Conversion was established in 2009 and funded by the Swedish Energy Agency, VINNOVA, Statkraft and Uppsala University [25]. The Lysekil wave

energy research site was established near Lysekil to evaluate the WECs' operation as a single unit and as a part of a cluster and interconnection to the grid by using power electronic converters and its effect on wave energy absorptions by the WEC [3]. The goal of this project is to test the concept of a linear generator in realistic conditions and over a long period of time, thereby fulfilling a serious dearth of established solution. The PTO consists of a linear generator placed on the sea bed and attached to the WEC on the surface, a point absorber, via rope. Several generators with their own WECs can be placed on the seabed and can be combined as groups and further by using cables on the seabed [25].

Fig. 4 shows the combination of the WEC and the linear generator (LG) used in the Lysekil project. Like the rotatory generator it is sealed; the fluid used is air so that there is no leakage out of and also into the generator body and has the end stop to reduce the damage to the body in case of extreme motion. The motion of the WEC mimics the motion of the waves and this eliminates the need to convert this motion to high speed, rotational motion. The generator is directly driven so there is no need for a gearbox, a regular part of the conventional PTO, which needs regular maintenance and has a high risk of failure. The spring at the bottom not only serves as a retracting force after the translator has been lifted during the wave crest but also stores energy temporarily and evens out power output [23].

Thus the challenge is the large investment costs for large structures and long-life mooring, since the project aims at looking for a solution that is able to operate for a longer period of time. However, using a linear generation there is no longer any need to convert the slow motion of waves to drive high speed, rotating generator [23].

Another challenge is to provide resistance to the downward forces on the generator. LG developed by Oregon State University has a 'deep-draught' spar to provide buoyancy to provide resistance to the upward force [11]. The LG developed by Uppsalla University has a spring at the bottom of the moving permanent magnet that has the same function.

For grid interconnection the transmission system for transmitting power to the grid must be able to operate with minimum losses, be robust and cost-effective and should influence the environment as little as possible. The optimum design will depend on the number of WECs, the transmission distance from the shore and legal issues. Further details for the electrical engineering considerations can be found in references [26,27]. A voltage source inverter (VSI) has been found to be more efficient than a current source inverter (CSI) [15]. The Lysekil team has considered an underwater substation for the conversion of the output from PTO suitable for grid interconnection with a combination of diode rectifier and VSI. The details can be found in reference [15]. The same reference also has suggested to investigate the use of back-to-back VSIs in future.

3.5. Cogeneration: combining electricity generation with purifying sea water

The Carnegie Wave Energy Company, an Australian company working on wave energy technology, is testing a new type of submerged point absorbers in the Perth project in Australia called CETO. Figs. 7 and 8 show the basic idea behind CETO WEC technology and its application in cogeneration respectively. It works by delivering high-pressure water to the shore which generates electricity by using turbines that are similar to those used in hydroelectric generation. The system is still in the testing phase but it is attractive because it can support cogeneration to produce desalinized water in an environmentally friendly way [28].

CETO is an excellent example of a project that utilizes the experiences from the projects in the UK and the Lysekil project. It uses a completely submerged WEC which can be classified as a wave activated body. The WEC can either be connected directly to a generation system to produce electricity off-shore or can be connected to water pipes to deliver high pressure water to the shore, as shown in Figs. 5 and 6. Electricity can then be generated by using off the shelf hydroelectric generation technologies and eliminates the need for special maintenance requirements and developing marine-qualified generators. Alternatively, CETO technology can also be used to support desalinization plants, as shown in Fig. 6. The WEC drives high-pressure water to the shore which is desalinized by standard de salinization equipment. These two can be combined to co-produce electricity and desalinized water. It also eliminates the need for undersea transmission [28].

The Perth wave project is thus an excellent example of how old experience can be used to facilitate the implementation of newer technologies. CETO brings together technologies used by earlier implementations; the WEC is a submerged type wave activated body and the off the shelf generator technologies can be utilized. It also has found new ways to tackle the challenges such as eliminating the need of underwater transmission systems. Furthermore, like the Lysekil project, environmental impact of the CETO was also studied and will be discussed in Section 4.

3.6. Cost and economic considerations

In order for a technology to be attractive in today's competitive market it has to be efficient and also cost effective. A competitive renewable energy source is described as one which is not only cheap, quick to implement and sustainable but also economical in terms of tariffs and the long-term returns on investments. This is very important when it comes to the choice of technologies. This is particularly more important in the case of wave energy as the environmental conditions and the range of power that a WEC is exposed to vary greatly. Initial reports on the potential of renewable energy represented the technologies in terms of rated power only. The rated power is not a very helpful quantity when it comes to knowing how much energy can be generated overtime and thus predicting how much revenue can be generated. Thus a holistic approach is required to come up with solutions that are technically and economically acceptable. Thus just like in case of conventional generation methods power density and the degree of utilization are important to characterize any type of fuel [29].

Before proceeding it is important to mathematically represent the terms which shall be used. The detailed derivations of these terms have been presented in reference [30].

3.7. Power density

The power density represents the power available per unit volume. Since the renewable energies are intermittent, power density varies over time. Fig. 7 shows a comparison between the available energy of conventional non-intermittent and renewable intermittent sources. Thus it can be seen that the available power density also varies with time. Power density is also dependent on the availability of the resource itself and also the obstacles it faces [29]. For example, the power density of sun is highest at noon and lower during other times of the day. Besides, the density will be much lower than normal if there are obstacles in the way of solar generators or there are clouds. Power density when combined with the degree of utilization can be a good projection of how much energy can be generated from a renewable source.

3.8. Degree of utilization and competitiveness of WECs

Usually the utility pays for the capital in terms of installed power and receives revenue in terms of yearly produced energy in

kWh. The *degree of utilization*, α, can be explained as follows:

$$\alpha = W/(P8760) \tag{2}$$

where, W is the yearly produced energy in kWh, P is the installed capacity in kW and 8760 is the hours in a year [30]. If the down time for maintenance is included the *degree of utilization* compares the power delivered to the grid with the installed power. The variations of available power over time must be considered when selecting a competitive renewable source and thus degree of utilization is highly useful for projecting how much revenues would be generated [29].

The degree of utilization for renewable sources varies with the location. For example, the degree of utilization for wind is as low as 18% in Pakistan [29], while its mean value for the whole world is 24.7% and it is as high as 29% for Sweden [30]. For conventional power plants, the degree of utilization is as high as 90% including shut down for maintenance [29].

Waves show much higher degree of utilization from solar and wind. This is because waves are produced by wind and are capable of transporting the energy across oceans virtually without any loss. The degree of utilization is higher near the coast where the distance from the land in the dominant wind direction is higher [29].

3.9. Investing in the renewable sources

To get a picture of how much the conversion costs we can use production *price per unit of electricity*, a, in USD/kWh. If we assume the interest rate as z, the present value of 'a' can be calculated as:

$$a = [1-(1+z)^{-n}]/z \tag{3}$$

where n is the number of years of investment.

One can estimate *allowed investment*, d, by relying on the fact that the income over 'n' and must be greater than the cost of a unit of energy weighted with maintenance and supervision cost, c, in USD/kWh. Hence allowed investment per unit of installed power can be calculated as [30]:

$$d/P = 8760\alpha(a-c)[1-(1+z)^{-n}]/z \tag{4}$$

The above equations determines the *total investment per unit of capacity* in terms of all important factors; investment time, utilization, interest rate, maintenance and price of electricity. By using (2) and inserting it into (4), one can arrive to an equation for 'd' independent of the installed capacity [30]:

$$d = W(a-c)[1-(1+z)^{-n}]/z \tag{5}$$

Fig. 8 shows how the present value for investment varies for different degree of utilization. It has been observed that long-term investment on conversion systems with higher degree of utilization is easier. For lower degree of utilization there is a need to develop strategies that involve subsidies. Once that has been done, the use of degree of utilization becomes more pronounced [30].

When evaluating renewable energy sources the degree of utilization has been recommended by researchers as the primary factor [29,30]. Evaluating waves on this criterion shows promising results. The degree of utilization is high which means it is an attractive long-term investment. The potential wave energy sources with an even higher possible degree of utilization must definitely be investigated [30].

Surely the generation of economic wave power is very attractive; there will be no noise or visual impacts unlike with the wind turbines as the wave-power generation takes place away from the inhabited areas. This form of power requires less area and has more output when compared with wind-energy technology [31].

4. Environmental considerations

The quest for sustainable energy is driven by a determination to look for sustainable methods of energy generation with the least environmental effects. So it is necessary to be on the lookout for the impacts of these renewable energy resources on the environment; the devices should not affect the existing flora and fauna and have to be adapted to the local conditions also [25].

4.1. Comparison with fossil fuel systems

All devices are expected to have some environmental impact. The effects of WECs can be directly compared with fossil fuels. What is interesting to note that is instead of having negative effects, WECs can have positive effects; they can reduce the amount of erosion of the shore landscape by extracting the energy out of the waves. The impact on aquatic organisms is very site specific and hard to predict but it can also support new colonization by becoming artificial reefs [32].

4.2. Hydraulic fluids

The Pelamis device uses a fluid-filled generator for PTO which has a high environmental risk if it leaks. But the Pelamis makes it highly unlikely by using two levels of protection at points where the leak is highly probable. The fluid is also biodegradable [1] and the fluid content and leakage is actively monitored. An anchoring system based on anchors and tethers are used currently to anchor the system. Unlike a vessel, where marine growth on the vessel causes drag, the effect of colonization of ocean life on the anchoring system on the Pelamis is negligible. The system is itself immune from any effects from growth of sea organisms except for a few components, for example the heat exchangers, where anti-fouling measures can be done [33].

4.3. Effects of WECs to the surrounding environment and ecosystems

Deploying WECs in off-shore locations introduces artificial structures in the ocean topography. This can affect the soft-bottom habitats in potentially a number of ways such as restructuring of the bienthic community, fish populations and accumulation of species on and around the deployed objects. Also, the objects can provide protection to organisms and organisms can grow on the structures themselves. It seems that the effects of WECs on the surrounding are fairly localized and can be mostly positive [34]. It has also been observed that the WECs can actually reduce shore erosions as they take the energy out of the waves as they reach the shore and waves are available almost all the time [31].

4.4. Results from practice

Special measures were taken in the Lysekil project to check the effects of the WECs on the existing environment on the project site. Sediment samples were taken before the start of the project and then from the Lysekil test site and a control site. The studies show that 68 species were present in significantly higher abundance than at the control area. No species were reported to be extinct. There was addition of some new species but none of them were dangerous and did not threat the existing species [3]. It was found out that some new organisms colonized the ropes and the point absorbers, and the WECs and the PTO system actually helped improving the biodiversity [35].

It was also found out that the colonization or biological fouling does not impact the performance of the WECs at all. The PTO and artificial structures attracted the sea organisms as artificial reefs, same as for the other WECs projects. Commercial fishing can be affected

from the installations but designing WECs and PTOs that support artificial reef and biological fouling wave energy parks can be used as protected areas and increase fish densities. Migratory birds do not seem to be affected as long as the devices are kept away from breeding colonies on the shore. The effects on sea life who rely on underwater noise to navigate, communicate, prey and avoid predators such as whales, seals and dolphins, are yet to be known and further investigation have to be done. Investigation must also be done on the effects of electromagnetic fields on the underwater species [35].

The commercial units of CETO installed for demonstration have shown good environmental impact; installation can be done on the sandy bottom so there is no effect on the reefs, devices are submerged so there is no visual impact, no lubricants or fluids are used so there is no leakage problem and it generates no in-water electricity that can harm sea life. However, a full environmental assessment is still required to understand and predict the effects of these devices on marine life and environment [36].

5. Remarks

Wave energy remains far behind other renewable energy resources in terms of implementation but it is as promising in terms of available power and reduced carbon capabilities. A scrutiny of different projects for wave energy conversion shows similarity in challenges faced for designing of a WEC and PTO systems. But scientists have come up with creative ways to solve them. Research in the beginning was focused on sea conditions and survivability but gradually increased to incorporate all areas including commercial and environmental aspects of the technologies. Environmentally WECs have been proven to support rather than damage ecosystems.

The most important challenge while implementing WEC technologies is converting a low-frequency and high-force input to an output which should be acceptable to the grid. Furthermore, it is important to investigate the conditions of the sea bed; a couple of projects have failed as the conditions of the sea bed were not determined, which resulted in irreversible damage to the WECs. Furthermore, maintenance of the WECs is also an important issue, especially for off-shore devices. Choosing the right WEC technology is also a challenge, but, as discussed in the introduction, methodologies exist for evaluating different technologies for implementation. But before implementing WEC, it is necessary to determine if the investment is economical or not.

Wave energy is a promising field, with a higher degree of utilization from solar and wind. It also has no visual and environmental impact. Yet it is still in infancy and requires more initiative and standardization. Hence, it is useful to outline the concerns and obstacles that are normally faced. More research must be encouraged to not only append to these concerns but to explore the areas that have yet to be touched. If successful, wave energy not only can cover the electricity demand for decades to come but also support development of ecosystems in the sea bed and even support purification of sea water into clean, drinkable water.

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